

**Ocean Surface Temperature Response to Atmosphere-Ocean
Interaction of the MJO**
*A component of Coupled Air-Wave-Sea Processes in the Subtropics
Departmental Research Initiative*

Christopher J. Zappa
Lamont-Doherty Earth Observatory of Columbia University
Ocean and Climate Physics Division
61 Route 9W
Palisades, NY 10964
Phone: (845) 365-8547 Fax: (845) 365-8157 email: zappa@ldeo.columbia.edu

Award Number: N00014-11-1-0853

LONG-TERM GOALS

We are part of a multi-institutional research team funded by the ONR-sponsored the ***Coupled Air-Wave-Sea Processes in the Subtropics Departmental Research Initiative***. The primary research goals of the program include: (i) Surface flux observations in regions of known coupled modes, (ii) Co-located observations of atmospheric and oceanic vertical structure and evolution, and (iii) Ocean mixed layer and marine atmospheric boundary layer dynamics, and interactions between these and the surface wave field, the free atmosphere, and the interior ocean. Our goals are to contribute innovative measurements, analyses and models of the sea surface temperature at length scales as small as a 1 meter up to 100's of kilometers. This characterization includes the skin SST, waves, wave breaking, and upper ocean processes.

OBJECTIVES

The Madden-Julian Oscillation (MJO) is an intraseasonal oscillation which is most closely identified with the tropical Indian and Pacific Oceans, characterized by an eastward progression of a large (~2000 km) pattern, extending from the equator into the adjacent subtropical belts, with enhanced and suppressed rainfall. In the context of this DRI, understanding the complex processes involved in locations such as the MJO as it passes over the eastern Indian Ocean are necessary steps for evaluating the modulation of SST and atmosphere-ocean feedbacks, for validating ocean and climate models, and for making prognostic assessments of oceanic circulation.

A recent MJO workshop [Sperber and Waliser, 2008] has suggested that observations are lacking for many important processes (e.g. convective momentum transport, moistening of the boundary layer, diurnal cycle of shallow convection, and surface fluxes). It also suggests the measurements are needed to provide insight into a variety of MJO characteristics including the transition to and from the convective phase including scale interactions with mesoscale systems, and the diurnal cycle over the land and ocean. The workshop highlighted that a better understanding of the vertical structure of the atmosphere, including clouds, moisture cycling, and related properties (e.g., long wave and shortwave radiation, humidity), is not adequately represented in simulations of the MJO.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2013		2. REPORT TYPE		3. DATES COVERED 00-00-2013 to 00-00-2013	
4. TITLE AND SUBTITLE Ocean Surface Temperature Response to Atmosphere-Ocean Interaction of the MJO A component of Coupled Air-Wave-Sea Processes in the Subtropics Departmental Research Initiative				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Lamont-Doherty Earth Observatory of Columbia University, Ocean and Climate Physics Division, 61 Route 9W, Palisades, NY, 10964				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 9	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

The broad science questions to be addressed by our program include the following:

- How do atmospheric boundary layer processes and sea-air coupling over the eastern Indian Ocean modulate the intensity and spatial extent of MJO and of higher frequency fluctuations?
- What regulates the sea-wave-air interactions and the response of the mixed layer during periods of MJO forcing?
- How do the near-surface profile characteristics evolve over the course of an MJO cycle and at higher frequency fluctuations?

Understanding the complex processes involved in locations such as the MJO as it passes over the eastern Indian Ocean are necessary steps for evaluating the modulation of SST and atmosphere-ocean feedbacks, for validating ocean and climate models, and for making prognostic assessments of oceanic circulation. Our science goals are directly related to the special focus areas of the DRI described above in Long-Term Goals.

Our science goals complement and parallel those of J. Moum of Oregon State. They plan to deploy a fully instrumented Chameleon turbulence profiler along with a bow-mounted CT chain to understand the upper ocean processes important to the MJO cycle from the R/V Revelle. Our science goals also complement and parallel those of J. Edson of the University of Connecticut who plans to make direct measurements of latent heat flux on the R/V Revelle, as well as more conventional rawinsonde launches in addition to turbulent air-sea fluxes from the ship during the IOP. Further, we expect to have interactions with the many PIs aboard the NOAA P-3 aircraft including Shuyi Chen and Qing Wang.

APPROACH

Lamont-Doherty Earth Observatory of Columbia University (LDEO) developed an airborne imaging system that utilizes both infrared and visible cameras to map the ocean surface SST and ocean surface processes. We build substantially on our accumulated expertise in sea surface processes and air-sea interaction. We are working within the larger team measuring and characterizing the ocean surface properties, namely SST. Airborne IR imagery will provide high spatial resolution calibrated SST variability. The image scale will be roughly 500 m to 1000 m (depending on altitude) with resolution of order 1 m. This team is contributing the following components to the primary sea surface imagery data gathering effort in LASP/DYNAMO:

- fast response, infrared (IR) imagery to characterize SST signatures including upper-ocean convection, freshwater lenses due to rain, Langmuir circulation, internal waves, ramping of near-surface stratification, etc. at scales of $O(1\text{m}-1000\text{m})$
- high resolution video imagery to record general ocean surface conditions and whitecap data using wide field-of-view to quantify scales of $O(1\text{m}-1000\text{m})$

With our added payload capacity on the NOAA P-3, thermal infrared (IR) imagery demonstrates the ocean surface processes that are relevant to atmosphere-ocean interaction. As the focus of the measurement module, we will implement a small sensitive uncooled IR camera to map the temperature structure of the ocean's surface. The FLIR SC655 is an un-cooled microbolometer focal plane array of 640 x 480 elements that are sensitive to 8.0-12.0 micron radiation. The microbolometer array performance will allow for the determination of temperature variability of less than 50 mK.

Additionally, we will deploy a JADE LWIR 570 Sterling-cooled Mercury-Cadmium-Telluride (MCT) focal plane array of 320 x 240 elements that are sensitive to 8.0-9.3 micron radiation. The MCT focal plane array performance will allow for the determination of temperature variability of less than 20 mK. The combination of cameras will allow us to capture a multitude of scales from $O(1\text{m} - 1000\text{m})$. Finally, an Imperx model Bobcat 2520 visible camera with 2500 x 2000 elements was deployed for high-resolution determination of the ocean surface structure.

We also deployed an up- and down-looking radiometer system to measure SST_{skin} aboard the R/V Revelle. The system includes two longwave narrow FOV Heitronics KT-15.82 TIR radiometer (8-14 microns for lower noise levels) instruments that are calibrated to better than 0.05°C . The upward-looking instrumentation will be used to discriminate real from apparent ice surface temperature variability. Apparent temperature variability in the infrared imagery may arise on partly cloudy days when both the radiatively-cold sky and radiatively-warm clouds reflect into the imager FOV. The overall system accuracy is $\pm 0.05^{\circ}\text{C}$ and can sense radiometric temperatures down to -80°C depending on the integration setting.

We also measured the waves with a single downward-looking Riegl model LD90-3100VHS laser altimeter boomed out from the jackstaff of the R/V Revelle. The Riegl output was heave compensated using the MotionPak from the direct covariance system also on the jackstaff.

WORK COMPLETED

In FY13, Lamont-Doherty Earth Observatory of Columbia University (LDEO) analysed the data taken during the measurement IOP for the P-3 that took place from 3 November 2011 through 15 December 2011 based in Diego Garcia. The overall objectives of the NOAA WP-3D (P-3) field campaign in LASP/DYNAMO are to address the basic science questions/hypotheses regarding air-sea interaction and tropical convection with its unique standalone suite of measurements, and to bridge observations from fixed locations on ships and islands.

We have presented our results at the MJO Field Data and Science Workshop, Kohala Coast, HI, USA in March 2013, at the ONR LASP DRI Data Workshop, Oregon State University, Corvallis, OR, USA in June 2013 and at the ONR Physical Oceanography Peer Review, Embassy Suites, Monterey, CA, USA in September 2012.

RESULTS

R/V Revelle Measurements

SST_{skin} was measured from the KT-15 system aboard the R/V Revelle during the 2nd, 3rd, and 4th legs. SST_{skin} shows a strong diurnal signal typically of $O(1^{\circ}\text{C})$ and is also nominally a cool skin layer for most of the nighttime as well as daytime when the insolation is not overly strong. At times, a warm skin layer can develop. We identified 103 rain events that averaged 1-hour duration and 15 mm. Composite normalized time series of all identified rain events (see Figure 1) show the direct response of air temperature (decrease of -2°C), of U_{10} relative to the surface currents (2 m s^{-1} increase), and of bulk water temperature (0.2°C decrease) to these precipitation events. All variables reach their peak anomaly at the peak SST_{skin} response. The mean change in SST_{skin} due to rain is a decrease 0.5°C (attenuated here due to bin averaging) that results in a distinct increase in the net heat flux of the ocean to the atmosphere of 50 W m^{-2} . SST_{skin} response was similar for all 3 observed MJO events. Response

during the Suppressed Phase (up to 0.8°C) was significantly greater than during Active Phase (less than 0.3°C) if the MJO. Heat flux response is strongest during the transition between Suppressed to Active Phase (up to 100 W m^{-2}). SST_{skin} cools by double the bulk response just a few 10 cm below and recovers significantly longer than the bulk response.

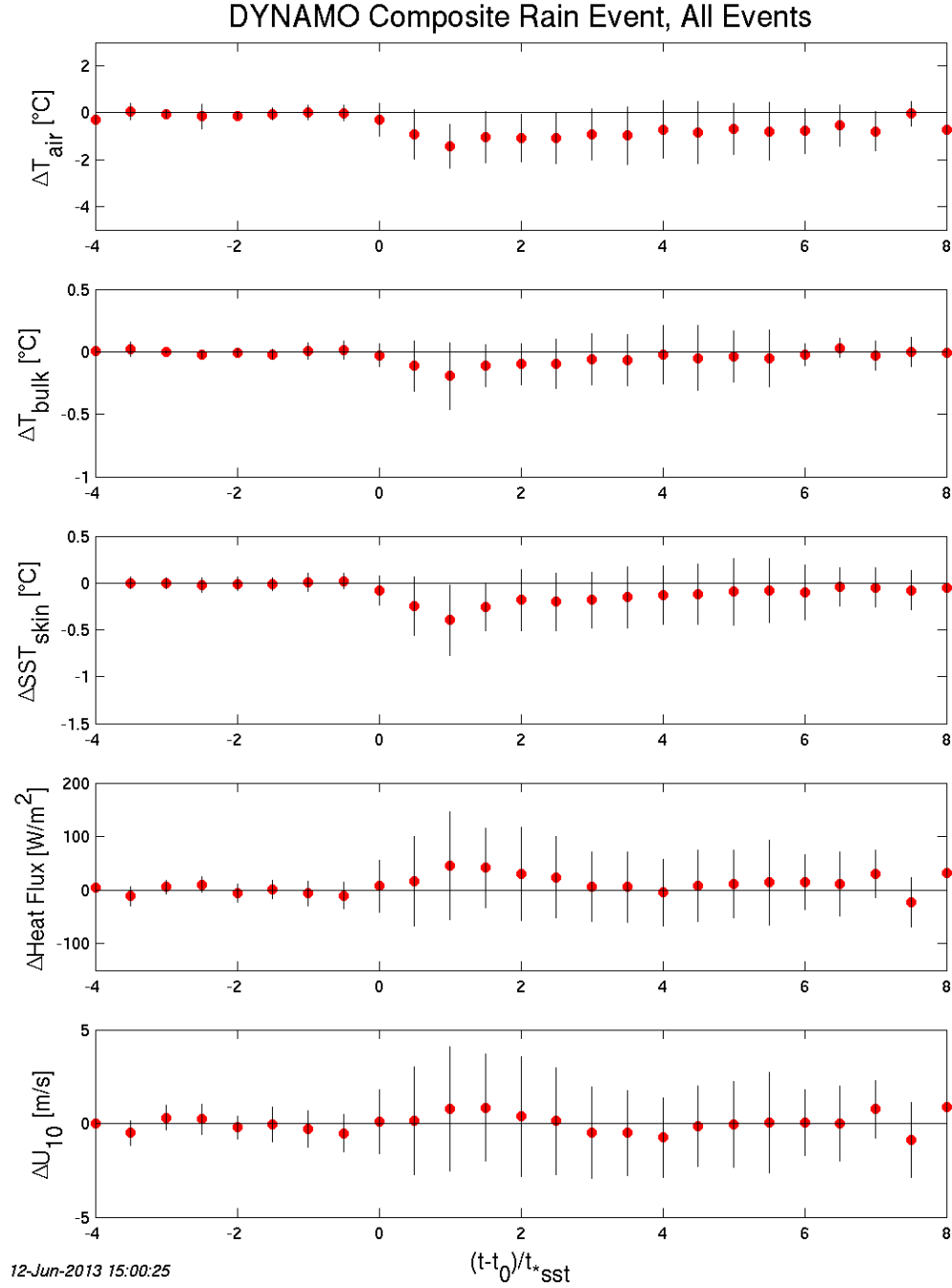


Figure 1. Composite normalized time series of the direct response to precipitation events of T_{air} , T_{bulk} (10 cm), SST_{skin} , net heat flux (including due to rain), and wind speed (U_{10}) from 103 identified rain events measured from the R/V Revelle for the 2nd, 3rd and 4th legs.

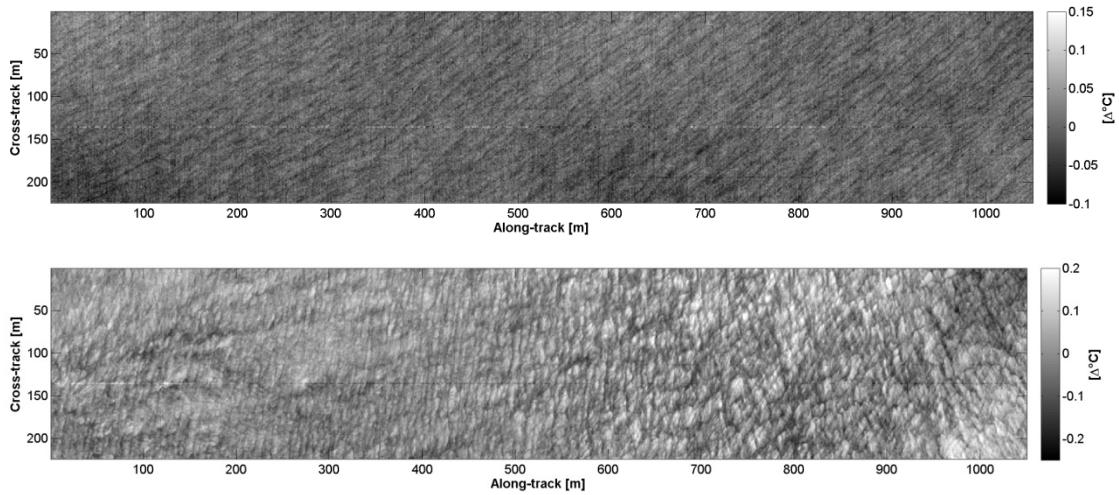


Figure 2. (Top) Infrared imagery of Langmuir circulation while crossing the convective front during the active phase of the MJO. The Langmuir circulation shows a small-scale temperature variability of $0.1\text{ }^{\circ}\text{C m}^{-1}$ with horizontal scales of $O(10\text{-}50)\text{m}$. (Bottom) Infrared imagery observations of the 2-D sea surface patchiness. The 2-D sea surface patchiness shows a small-scale temperature variability of $0.2\text{ }^{\circ}\text{C m}^{-1}$ with horizontal scales of $O(10\text{-}50)\text{m}$.

During the active phase of the MJO, we observed onset equatorial convection with strong winds in a moist environment. We have multiple instances that build up a consistent picture of the evolution of the sea surface patchiness and upper ocean structure during convective events. During these convective events, a large-scale temperature change of up to $1.0\text{ }^{\circ}\text{C}$ across the front. Embedded within this strong temperature change across the convective front exists a distinct coherent Langmuir circulation structure. The Langmuir circulation shows a small-scale temperature variability of $0.1\text{ }^{\circ}\text{C m}^{-1}$ with horizontal scales of $O(10\text{-}50)\text{m}$ (see Figure 2 Top). Observations show that the sea surface variability quickly evolves from its initial state to a system dominated by the linear 1-D features of Langmuir circulation as the convective front (high precipitation / high winds) propagates over a specific location, to a system behind the convective front (less precipitation / moderate winds) where the sea surface patchiness evolves to 2-D features that appear without the strong forcing. The 2-D sea surface patchiness shows a small-scale temperature variability of $0.2\text{ }^{\circ}\text{C m}^{-1}$ with horizontal scales of $O(10\text{-}50)\text{m}$ (see Figure 2 Bottom). The Langmuir circulation organizes the fresh water rain during the front and sea surface patchiness evolves after the strong winds subside. These features are related to both the fresh water lenses as well as sea surface patchiness. Goal is to measure the scales of coherent structure to compare with the MO Length scale.

Evolution of the short fetch gravity wave field and wave breaking through the convective events is important to the response of the upper ocean. The leading edge of convective front is typically associated with an initial increase in wind stress from the preceding calm conditions (Figure 3a). Wind stress slowly increases peaking at 0.7 N m^{-2} . The peak in significant wave height lagged that of wind stress by 2 to 3 kilometers. The wave spectrogram shows the abrupt appearance of a narrowband wind wave field at $0.25\text{-}0.30\text{ Hz}$ (3-4s period) at the convective front, indicative of very young seas (low

ratio of phase speed to wind speed, $c_p / U_{10} = 0.5$). Thereafter, the spectrum of the wind waves broadened in frequency and increased in intensity, masking the original two-component swell.

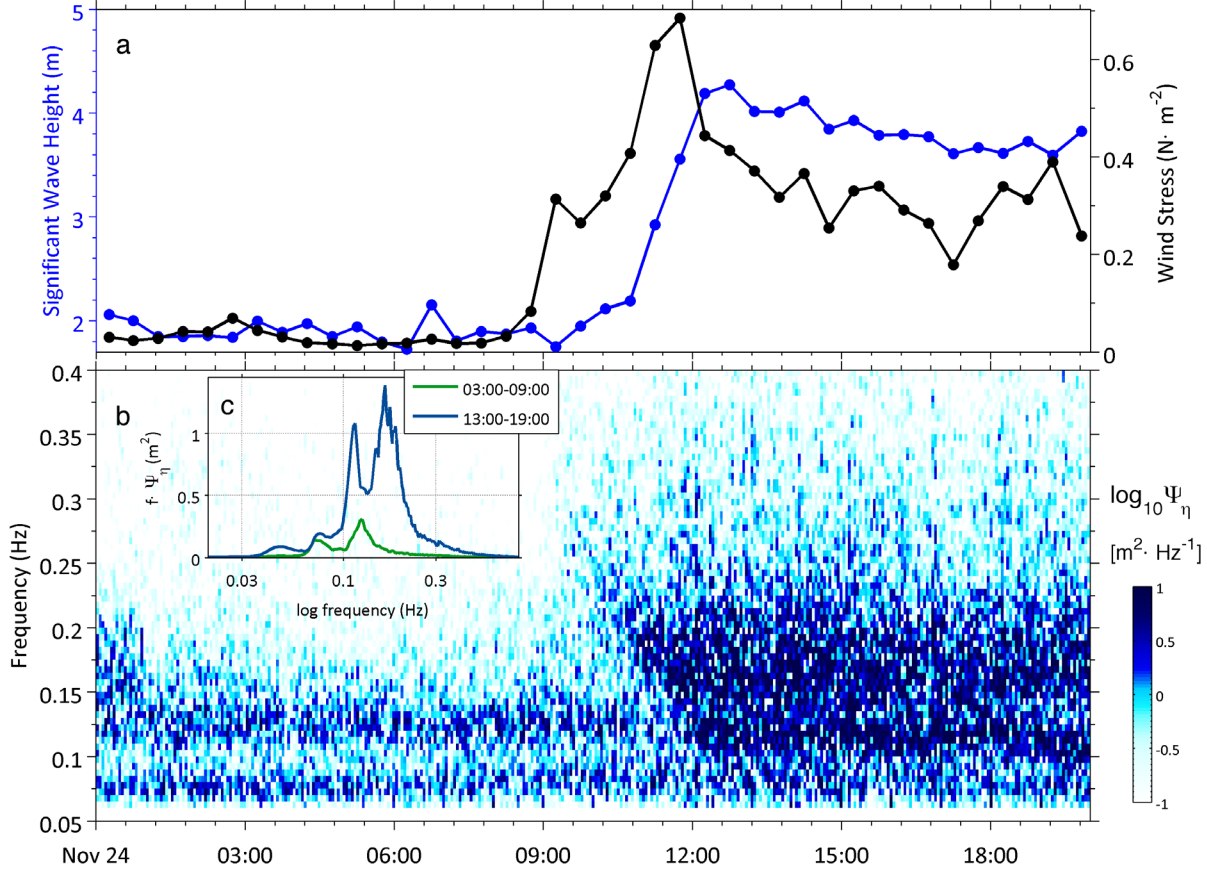


Figure 3. Time series of wind and waves at Revelle showing the arrival of convective front during MJO2. (Top) a) Wind stress (black) and significant wave height (blue) as measured from motion-corrected laser altimeter. (Bottom) b) Spectrogram of wave height. (Bottom Inset) c) Averaged spectra (in variance-preserving form) representing periods 6 h prior to the arrival of the wind burst (03:00-09:00) and 6 h following (13:00-19:00).

A more direct comparison of wave states before and after the convective is seen in individual spectra (Figure 3c – here in variance-preserving form, where equal areas represent equal energies). These emphasize the amplification of the higher-frequency wind wave field and show the change in the lower-frequency swell components. The initial 13 s period waves lingered after the wind burst’s arrival, but the 8 s swell diminished, replaced by a 9 s swell from due west, the direction of convective front.

The contribution of the growing and breaking wind waves was significant for the young seas across the convective front and diminishes behind the convective event (see Figure 4). There is no evidence of enhanced breaking ahead of the front. Note that wave age plays a significant role in wave breaking.

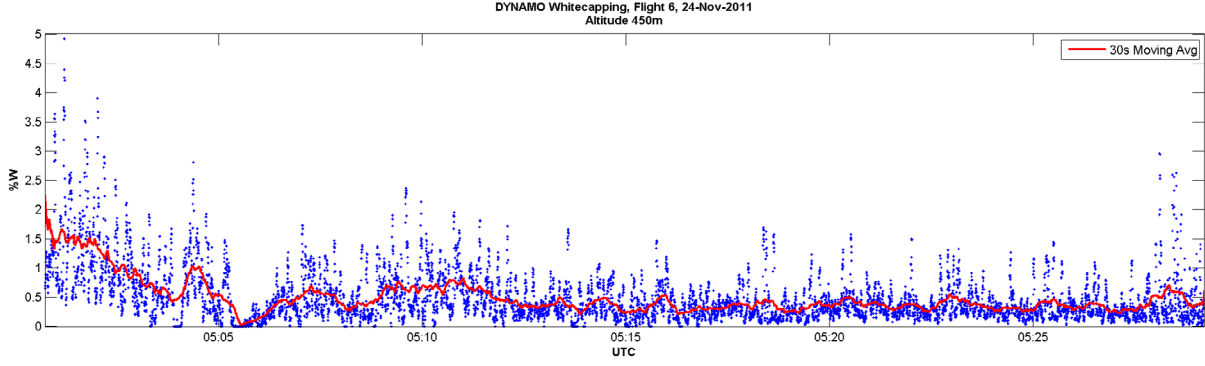


Figure 4. Whitecapping measured from the P-3 across a convective front. The contribution of the growing and breaking wind waves was significant for the young seas across the convective front and diminishes behind the convective event. There is no evidence of enhanced breaking ahead of the front. Note that wave age plays a significant role in wave breaking.

Langmuir circulations of very different spacings and persistence have so far been observed, but generally there seem to exist more unstable Langmuir circulations of smaller scales that occur between more stable ones with larger scales [Leibovich, 1983]. Craik and Leibovich [1976] developed the Craik-Leibovich set of equations (CL II) to describe the underlying process. The flow is governed by the dimensionless Langmuir number, La [Leibovich and Paolucci, 1981], representing the ratio of viscous forces, e.g., the diffusion of downwind viscosity and inertial forces which produce the vorticity by vortex tilting and stretching by the effect of waves [Thorpe, 2004]. In the case of monochromatic waves with a fixed frequency f , wave number k , and amplitude a , the Langmuir number can be defined as [Leibovich and Paolucci, 1981]:

$$La = \left(\frac{\nu_t^3 k^2}{f a^2 u_*^2} \right)^{1/2}$$

Where, ν_t is the eddy viscosity, k is the wind-wave number, f is the wind-wave frequency, a is the wind-wave amplitude and u_* is the friction velocity. These equations show the coupling of two main features of transport of momentum across the air-sea interface: Langmuir circulations (LCs) develop because of the interaction of surface stress (friction velocity u_*) and surface waves (Stokes drift u_s). La represents the ratio of the diffusion of streamwise vorticity to the production of streamwise vorticity by the effects of the Stokes drift.

Both Leibovich and Paolucci [1981] and Melville et al. [1998] presented a stability diagram of dimensionless wave numbers $k_{LC} = k_{LC}/k_{wave}$ against inverse Langmuir numbers La^{-1} . Here, k_{LC} is the “wave number” obtained from the spacing of Langmuir streaks and k_{wave} is the wave number of the wind-waves. The inverse Langmuir number can be regarded in analogy to the Rayleigh number. The Rayleigh number describes the relationship between buoyancy and viscosity in the case of heat convection. Accordingly, La^{-1} describes the quotient of inertial and viscous forces in CL II theory. Consequently, the flow is stable for very small La^{-1} and becomes unstable for larger La^{-1} . In Figure 5, the data points obtained here are compared to the global stability boundary that is found for constant Richardson numbers ($Ri = 0$) while varying Langmuir number La and wave number k [Leibovich and Paolucci, 1981] and the values obtained by Melville et al. [1998]. The global stability boundary developed by Leibovich and Paolucci [1981] is derived from the time of the onset of instability. The measurement of Melville et al. [1998] is correspondingly made at the onset of Langmuir circulations. In contrast, the values obtained here originate from an equilibrium state with both wave field and wind

stress constant in time. A comparison still shows good agreement and follows the trend suggested of the neutral stability theory by *Leibovich and Paolucci* [1981]. The obtained values for La^{-1} are located in the unstable regime as expected. For higher inverse Langmuir number, La^{-1} , we observe higher normalized wavenumber compared to *Melville et al.* [1998] data that is for onset of waves and Langmuir circulation and recent data from [*Schnieders et al.*, 2013] that is for fully developed wave field.

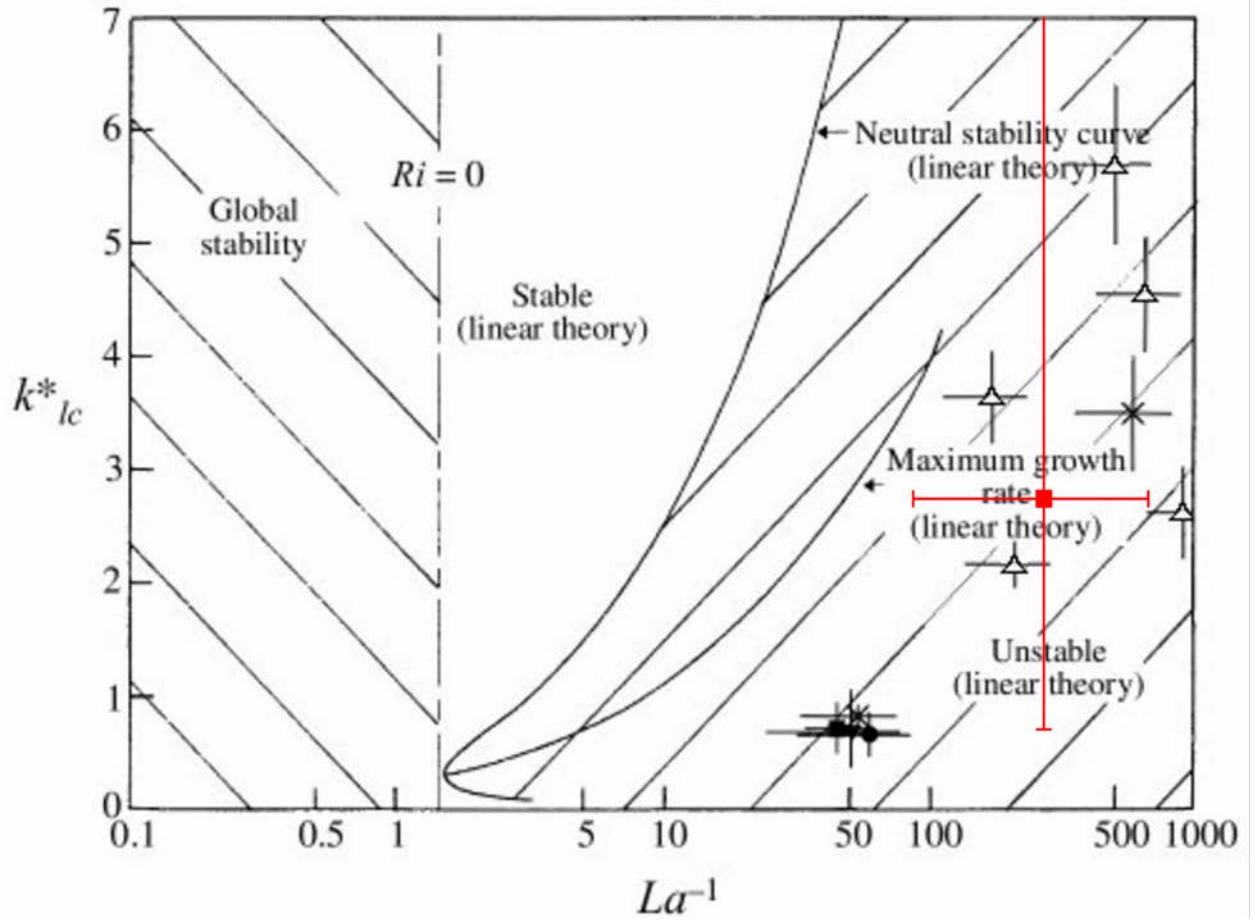


Figure 5. Non-dimensional Langmuir wavenumber, k_{lc}^* , against inverse Langmuir number, La^{-1} . Neutral stability theory by *Leibovich and Paolucci* [1981] compared with the data obtained by [*Melville et al.*, 1998] and the data measured at WRL under the presence of mechanical waves (open triangles) and the data from Aeolotron (crosses). Red square is for the data during this study.

IMPACT/APPLICATIONS

Understanding the complex processes involved in locations such as the MJO as it passes over the eastern Indian Ocean are necessary steps for evaluating the modulation of SST and atmosphere-ocean feedbacks, for validating ocean and climate models, and for making prognostic assessments of oceanic circulation.

REFERENCES

- Craik, A. D. D., and S. Leibovich (1976), A rational model for Langmuir circulations, *J. Fluid Mech.*, *73*, 401–426.
- Leibovich, S. (1983), The form and dynamics of Langmuir circulations, *Annual Review Fluid Mechanics*, *15*, 391–427.
- Leibovich, S., and S. Paolucci (1981), The instability of the ocean to Langmuir circulations, *J. Fluid Mech.*, *102*, 141–167.
- Melville, W. K., R. Shear, and F. Veron (1998), Laboratory measurements of the generation and evolution of Langmuir circulations, *Journal of Fluid Mechanics*, *364*, 31–58.
- Schnieders, J., C. Garbe, B. Peirson, G. Smith, and C. J. Zappa (2013), Analyzing the footprints of near surface aqueous turbulence - an image processing based approach, *Journal of Geophysical Research – Oceans*, *118*, 1272–1286, doi:10.1002/jgrc.20102.
- Sperber, K. R., and D. E. Waliser (2008), New approaches to understanding, simulating, and forecasting the Madden-Julian Oscillation, *Bulletin of the American Meteorological Society*, DOI:10.1175/2008BAMS2700.1, 1917–1920.
- Thorpe, S. A. (2004), Langmuir circulation, *Annu. Rev. Fluid. Mech.*, *36*, 55–79, doi:10.1146/annurev.fluid.1136.052203.071431.